CASSINI TRAJECTORY DESIGN DESCRIPTION

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ABSTRACT

The Cassini spacecraft will be the first one to visit the Saturnian system in more than two decades after the unprecedented flybys of the Voyager spacecraft in 1980 and 1981. Different from Voyager, the Cassini spacecraft will carry a probe, provided by the European Space Agency, that will be released into the Titan atmosphere relaying science data to the orbiter. The orbiter will store the probe data and will transmit it back to Earth at a later time. Another major difference from Voyager, in terms of its science return, is that Cassini will investigate Saturn, its rings, satellites, and magnetosphere for four years.

The Cassini mission is scheduled for launch in October 1997 using the Titan IV/Centaur with upgraded Solid Rocket Motors (SRMU). The launch will be from the Kennedy Space Center (KSC) launch complex 40 or 41. The spacecraft will be injected initially into the inner solar system after the Centaur upper stage completes its second burn which lasts approximately eight minutes. Following this burn, the spacecraft and the upper stage take different paths since the later initiates the Collision and Contamination Avoidance Maneuver (CCAM) to avoid impacting either Venus or the spacecraft. About 3 to 4 weeks after launch, the spacecraft performs its first Trajectory Correction Maneuver (TCM) to correct for injection dispersions. Because the launch vehicle cannot provide enough energy to fly a direct trajectory to Saturn, Cassini will fly a Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory to increase the energy of the trajectory. The spacecraft will be Sun pointed while it flies within one AU allowing the High Gain Antenna (HGA) to shade the rest of the spacecraft. During this time, communication with Earth will be achieved using the Low Gain Antennas (LGAs).

INTERPLANETARY TRAJECTORY

The data provided for the following description of the trajectory sequence of events apply only to the reference trajectory which is considered to be the trajectory for the opening of the nominal launch period. A table of mission events is presented in Table 1. The complete interplanetary trajectory is illustrated in Figure 1, and the inner solar system trajectory in Figure 2. If

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considering a trajectory other than the reference trajectory, some adjustments will have to be made to information such as dates, altitudes, and maneuver magnitudes, etc.

Table 1. Mission Events

Mission Events	Start Date	Days from Launch	Comments
Launch	6-Oct-97	0	C3 = 18.1 km2/s2
APHELION	1-Nov-97	26	Sun range = 1.02 AU
DSM	16-Mar-98	162	ΔV = 0 m/s; ΔV>0 for launch dates after 10/25/97
PERIHELION	23-Mar-98	169	Sun range = 0.68 AU
Venus flyby	21-Apr-98	198	Altitude = 300 km; Velocity = 11.8 km/s
HGA	21-Nov-98	417	On when Sun-s/c-Earth angle < 30° at 1.5 AU
DSM	2-Dec-98	423	ΔV = 466 m/s
APHELION	4-Dec-98	424	Sun range = 1.58 AU
LGA	3-Feb-99	485	Thermal constraints restrict HGA usage
Venus Flyby	20-Jun-99	622	Altitude = 2207 km; Velocity = 13.0 km/s
PERIHELION	27-Jun-99	629	Sun range = 0.72 AU
Earth Flyby	16-Aug-99	680	Altitude = 517, Velocity = 19.1 km/s
HGA	2-Sep-99	696	On permanently
• Conjunction	13-May-00	950	
• Opposition	28-Nov-00	1149	Gravity Wave Opportunity
Jupiter flyby	30-Dec-00	1181	Altitude = 141 Rj; Velocity = 11.5 km/s
• Conjunction	7-Jun-01	1340	
• Opposition	16-Dec-01	1532	Gravity Wave Experiment - opportunity ± 20 days
• Conjunction	21-Jun-02	1719	
• Opposition	27-Dec-02	1908	Gravity Wave Experiment - opportunity ± 20 days
• Conjunction	1-Jul-03	2094	
SCIENCE ON	25-Dec-03	2271	Science turn-on 6 months before arrival.
• Opposition	4-Jan-04	2281	Gravity Wave Experiment - opportunity ± 20 days
SOI	25-Jun-04	2454	ΔV = 625 m/s
• Conjunction	8-Jul-04	2467	
PRM	10-Sep-04	2531	ΔV = 326 m/s
Probe Separation	6-Nov-04	2588	
ODM	8-Nov-04	2590	ΔV = 57 m/s
Probe Entry	27-Nov-04	2609	
Titan 1 flyby	27-Nov-04	2609	Altitude = 1500 km; Velocity = 5.9 km/s
EOM	25-Jun-08	3915	End of 4-year tour

The perihelion of the initial orb _ is 0 . 68 AU and is the closest the space craft flies to the sun. This perihelion occurs on March 23, 1998. The first Venus encounter will be on April 21, 1998, 198 clays after launch. The Venus flyby trajectory is shown in Figure .3. The spacecraft (S/C) will approach Venus from the Sun direction. Closest approach occurs in the Sun occultation zone which will last about 16 minutes. At closest approach, the altitude will be 300 km, which is the minimum allowed altitude, and the velocity relative to Venus will be 11.8 kill/S. Targeting accuracy will be improved using two '1' CMs, 60 and 20 days before closest. approach, and a clean-up maneuver 20 days after the flyby.

A Few days before aphelion of the second orbit, a deterministic maneuver or Deep Space Maneuver (DSM) will be performed to reduce perihelion and set the trajectory for the second Venus flyby, The magnitude of this maneuver ranges from 350 m/s to 470 m/s depending on the launch energy and the launch date. This maneuver dcc~-eases through the entire launch period.

The second Venus flyby will occur on June 20, 1999, 424 days after the first. Venus encounter. The Venus-2 flyby trajectory is shown in Figure 4 . Venus will be approached from the anti-Sun direction. At closest approach, the altitude will be 2207 km, and the velocity relative to Venus will be 13 km/s . Targeting maneuvers will take place 60 and 2.0 days before closest approach, and a maneuver 10 days after the flyby . This maneuver includes the necessary Earth avoidance bias . Perihelion of the second orbit occurs a week after the second Venus flyby on June 27, 1999 at a distance of 0.72 AU from the Sun.

The geometry of the VVEJGA trajectory is very unique since it. provides the opportunity of a double flyby, Venus -2/Earth. The Earth flyby will occur 56 days from the Venus-2 flyby on August_ 16, 1999. The Earth flyby trajectory is shown in Figure 5. The Earth will be approached from the Sun direction, The altitude at. closest app]-each will be 517 km, and the Earth-relative velocity will be 19.1 km. Trajectory correction maneuvers will take place 30 and 10 days before closest approach, and a clean-up maneuver '20 days after the flyby,

The Jupiter flyby will occur on December 30, 2000 with an altitude of 141 Jupiter radii (10.1 million km), and a velocity relative to Jupiter of 11.6 km/s. The flyby altitude is dictated by gravity-assist. considerations. Lower Jupiter flyby altitudes would result in substantial Delta-Velocity (AV) penalties. TCMs will be performed 80 and 20 days p]-it)]- to the flyby for- targeting purposes, and 70 days after the flyby to correct_ for navigation errors . The science performed by Cassini before the Saturn app~-each phase is limited mainly to gravitational wave searches during three successive oppositions beginning December 2001 .

SATELLITE TOUR

Saturn orbit insertion (S01) occurs June 25, 2004, " 6.7 years after launch. This arrival date enables a distant Phoebe flyby 18 days before SOI. The orbit insertion maneuv wi11 place the spacecraft in an initial orbit with a periapsis radius of 1.3 Saturn radii, which is the closest the spacecraft gets to Saturn through the entire orbital tour, a period of 152 days, and an inclination of 17° with respect to Saturn's equator. The initial orbit is designed to target the combined orbiter/probe spacecraft to Titan with the proper approach speed and accuracy. On November 6, 2004, approximately four months after SOI, the Huygens Titan probe will be separated from the orbiter. Two days after separation, the orbiter performs the Orbit Deflection Maneuver (ODM) to ensure that, the orbiter will not follow the probe into Titan's atmosphere and to establish the proper geometry for probe data relay. Probe entry occurs at the first Titan encoun - on November 27, 2004.

The orbital tour lasts 4 years and consists of 63 Saturn orbits in various orientations, with orbital periods ranging from 7 to 152 days, and Saturn periapsis ranging from about 1.3 to 7.6 Saturn radii. Orbital inclinations with respect to Saturn's equator range from 0° to 76°, providing opportunities for ring imaging, magnetospheric coverage, and radio (Earth), solar, and stellar occultations of Saturn, Titan, and the ring system. A total of 33 close Titan flybys occur during the baseline tour; these are to be used for gravity assist. cent.rc)l of the Saturn orbits as well as for Titan science acquisition. The spacecraft is also targeted for 4 close flybys of selected icy satellites, and makes a total of 29 more distant satellite encounters. Figure 6 shows all tour orbits in a rotating coordinate system in which the Sun direction is fixed. The broad range of different orbit orientations allows detailed survey of the magnetosphere and atmosphere of Saturn. Since the Figure has been projected onto the Saturn equatorial plane, the inclination of the orbits is not apparent. At this early stage, there are many factors which may eventually cause the tour profile to diverge from the one presented here.

The baseline tour concludes in June, 2008, for a total mission duration of 10.7 years. Nothing in the design of the tour precludes an extended mission,

LAUNCH PERIOD

The current nominal launch period of the primary Cassini trajectory opens on October 6, 1997 and closes on October 30, 1997 providing a 25-day launch period. A contingency launch period might be included depending on performance and spacecraft. considerations. The opening of the nominal launch period is chosen to be the earliest launch date for which mission performance requirements are met and the Earth flyby altitude is not. lower than 500 km. Lower altitudes than this will result in undesirable penalties in satisfying Earth swingby requirements. The close of the nominal launch period is due to an operational constraint imposed by the increase in magnitude of a required maneuver in the launch-to-Venus leg of the trajectory. This maneuver increases in magnitude at, a rate of about 23 m/s per day and it. reaches a value of about 100 m/s on Oct. 30, 1997. Saturn arrival date is Constrained by launch vehicle and trajectory performance. Moreover, the probe mission must be at least.

15 days before, or 40 days after, a solar conjuction. Saturn arrival is also constrained by the interval in which the probe mission is prohibited. This maps back to an interval in which SOI is forbidden.

MISSION PERFORMANCE

Mission performance is measured in terms of End Of Mission (EOM) bipropellant ΔV, defined as the amount of bipropellant ΔV capability after completion of the four year satellite tour. Figure 7 shows the injection real-gin and EOM ΔV as a function of launch date. For launch dates from Oct. 6 to October 24, a local optimum trajectory exists. For launch dates beginning on Oct 25, the local optimum trajectory does not. exist, any longer. The trajectories shown for these later launch dates are for a fixed C3 (injection energy per unit mass) of 17 km^2/sec^2. As a result, these! trajectories are not optimal trajectories. A very detailed analysis of the launch /arrival space is being conducted to identify the best, performing trajectory to fly for the different launch dates through the launch period. A more complete description of this study can be obtained from the " CASSINI 1997 VVEJGA Trajectory haunch/Arrival Space Analysis".

Table 2 shows the mass summary for the primary mission with a launch date Oct. 6, 1997. Table 3 shows a propellant consumption profile throughout the mission for a launch date Oct. 6, 1997 and a C_3 of 18.1 km^2/s^2. A sample EOM ΔV is also illustrated in table 3. Cassini's 3132 kg of total propellant is used for deterministic and statistical (navigation) maneuvers, attitude control, line clearing maneuvers, and science turns. TCM's are either deterministic or statistical, and occur during both the interplanetary and satellite tour phases of the mission. The propellant consumption was computed from the rocket equation.

SECONDARY AND BACKUP TRAJECTORIES

To recover from posible launch delays arising from unavoidable schedule slips, t_he Cassini project has selected a set of secondary and backup mission opportunities, shown in Table 4 . These trajectories all make use of the Venus -Earth -Earth Gravity Assist (VEEGA) concept. Secondary missions are allowed to have a launch date less than six months after the primary mission. These missions protect against. launch slips that occur after hardware delivery, and can be diagnosed and fixed within a short time. Science return can be degraded slightly in light of the? competing pressure to launch the spacecraft if a problem delaying t_he primary mission is identified and solved. Backup missions are required to be launched at least six months after the primary mission opportunity, and to have the same science return profile as the primary mission. Backup missions are kept in the mission set to protect against launch slips from programmatic or technical issues tha - cause a long launch delay.

The current mission set contains two secondary mission opportunities, launching in Decembe - of 1997 and March of 1998, Figures 8 and 9. The first of these missions launches on a VEEGA December 97 trajectory, arriving at Saturn in October of 2006. The trajectory performance is sufficient in this case to allow no degradation to the science return. That is, the mission contains a full 4-year tour with 35 Titan flybys. The significant difference between this mission and the primary is a longer interplanetary cruise time, although the ring orientation with respect to the sun degrades over time. The cruise is two years longer after a launch delay of only 3 months. The other secondary mission, an EVEEGA March 98 trajectory (Figure 10), is launched onto a one-year Earth return orbit, which phases into the backup VEEGA March 99 trajectory. This backup VEEGA Trajectory can also be attained by launching the spacecraft in March of 1999, towards Venus. Both the March 1998 EVEEGA and the March 1999 VEEGA trajectory, arrive at Saturn in December of 2008.

The secondary and the backup trajectories have enough ΔV performance to carry out the mission with no degradation. However, the longer cruise times cause a change in the power available due to the degradation of the Radioisotope Thermoelectric Generator (RTG) power source. The available power level for the worst secondary mission at Saturn arrival is roughly equal to that available for the primary mission at EOM (SOI + four years). This results in fewer instruments being allowed to operate at a given time, or less engineering support to a suite of instruments.

Table 2. Cassini Mission Mass Summary [1] for SRMU performance.

		Mass (kg)
Dry Spacecraft (Orbiter) Allocation		2150
Probe Interface Hardware Allocation		46
Probe Allocation		306
Bipropellant (constant, load through launch period)		3000
Holdup and Residuals = 81 kg		
Required for ΔV = 2829 kg (I_{sp} = 308s)		
Margin = 90 kg		
Hydrazine		132
Attitude and Articulation Control System (AACS)	46 kg	
Required for ΔV = 52 kg (I_{sp} = 215s)		
Margin = 34 kg		
Total Wet Spacecraft (including probe)		5634
Launch Vehicle Adapter Allocation		190
Total Injected Mass		5824
Titan IV (SRMU)/Centaur Capability		6234
Injection Margin		410

[1] Openning of launch period on Oct. 6, 1997.

[2] Based upon NASA Lewis Research Center (LeRC) performance quotation for Cassini (Nov. 17, 1992) for a C_3 of 18.1 km^2/s^2. Includes 262 kg with variable launch azimuth, mission peculiar hydrazine burn-off of 18 kg, and 181 kg LeRC manager's reserve. Performance based on a dispersed FMH constrain_ 400 $BTU/ft^2/hr$

Table 3. Propellant Consumption Profile

	ΔV (m/s)	Isp (Sec)	Initial Mass (Kg)	Delta Mass (Kg)
Adapter drop			5824	190
DSM 1	0	308	5634	
DSM 2	466	308	5634	805
I/P NAV TCM Bipropellant	191	308	4829	296
Pre-SOI AACS drop			4533	31
SOI	548	308	4502	-14-1
SOI Delay + Gravity Loss	76	308	3755	94
PRM	326	308	3661	3"/5
First Orbit TCM Bipropellant	38	308	3287	41
Probe Release (PR)			3245	306
ODM	57	308	?.939	55
Deterministic Tour Biprop.	200	308	2884	185
Tour NAV TCM Bipropellant	271	308	2699	232
Tour NAV TCM Hydrazine	43	215	2468	50
Post-SOI AACS drop			2418	15
TOTALS	2217			3422

EOM Bipropellant/Hydrazine ΔV Margin (m/s) : 115/31

Total Usable Bipropellant required for nominal (Kg)	2829
Total Usable Bipropellant left at EOM (Kg)	90
Total Mission Bipropellant	3000
Total Usable Hydrazine required for nominal (Kg)	96
Total Usable Hydrazine left at EOM (Kg)	34
Total mission Hydrazine (Kg)	132

'1'able 4 Secondary and Backup Trajectories

Classification	Secondary	Secondary/Backup
Trajectory Type	VEEGA	EVEEGA/VEEGA
Launch Period	12/5/9"/ -12/22/9"/	3/?.0/98 - 4/6/98 3/19/99 - 4/5/99
Arrival Date	10/13/2006	12/22/2008
Cruise Duration (years)	8.8	10,8/9.8
Satellite 'l'our (years)	4	4

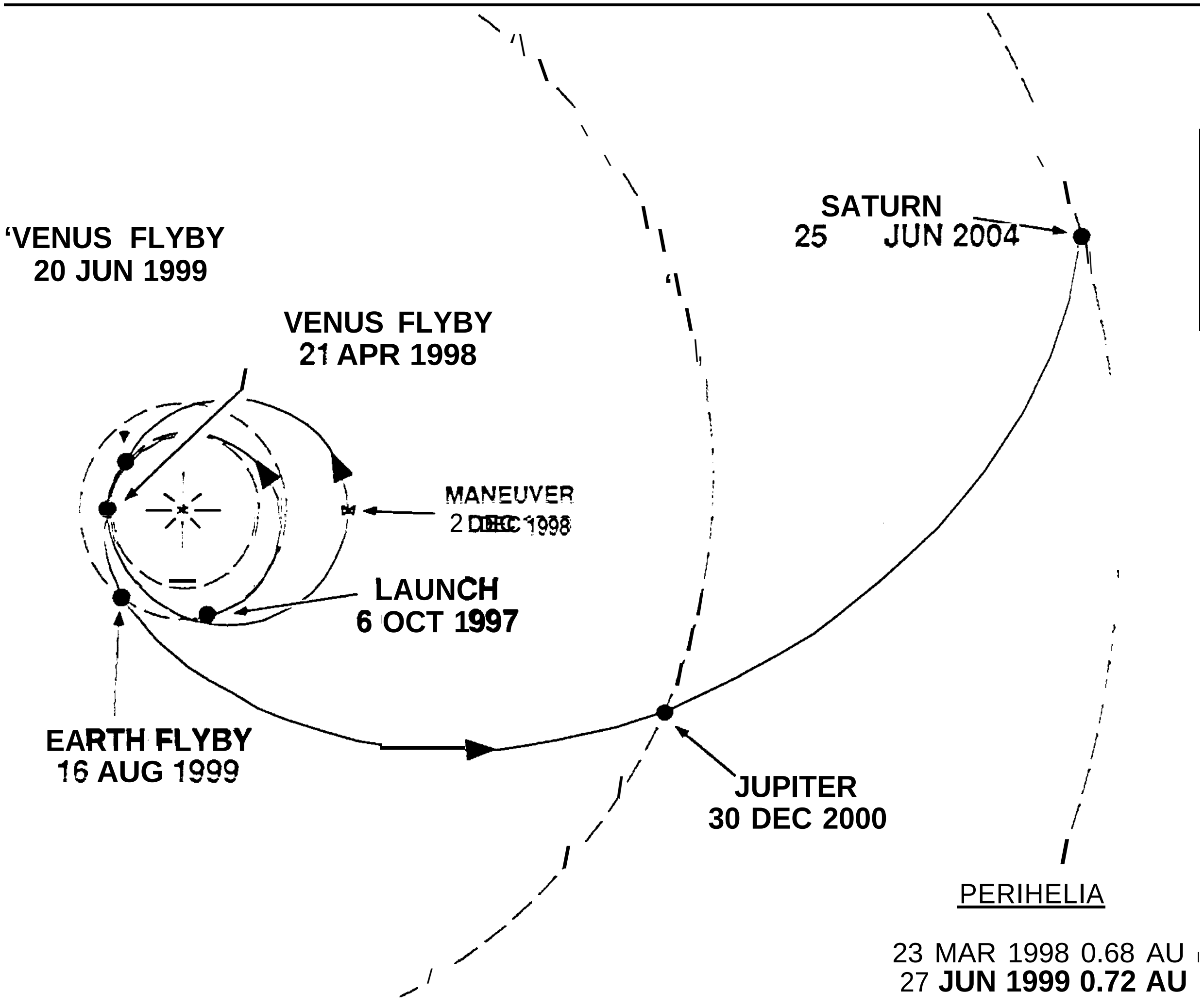

Fig. 1 VVEJGA Interplanetary Trajectory

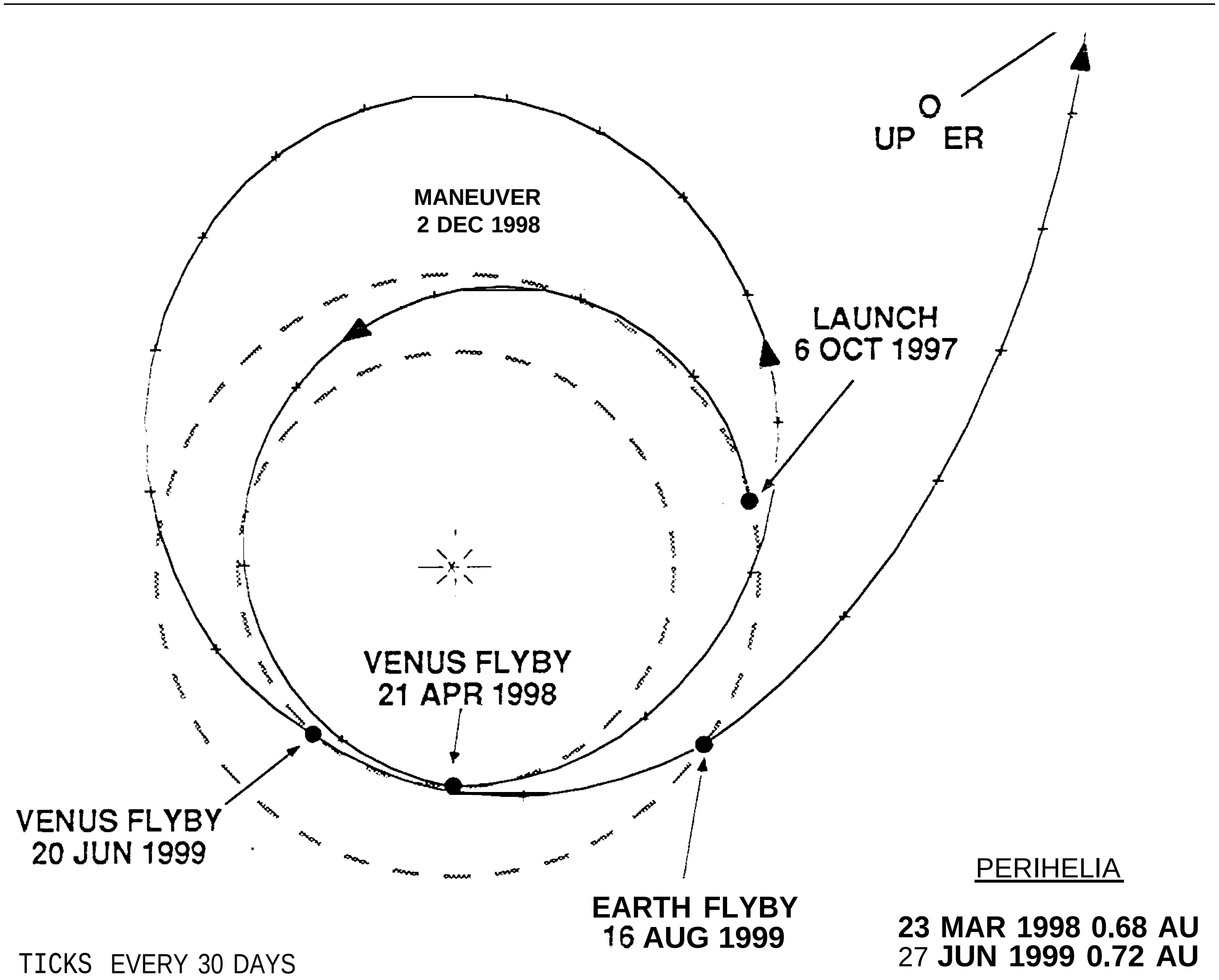

Fig. 2 **VVEJGA** - Inner Solar System ***Trajectory***

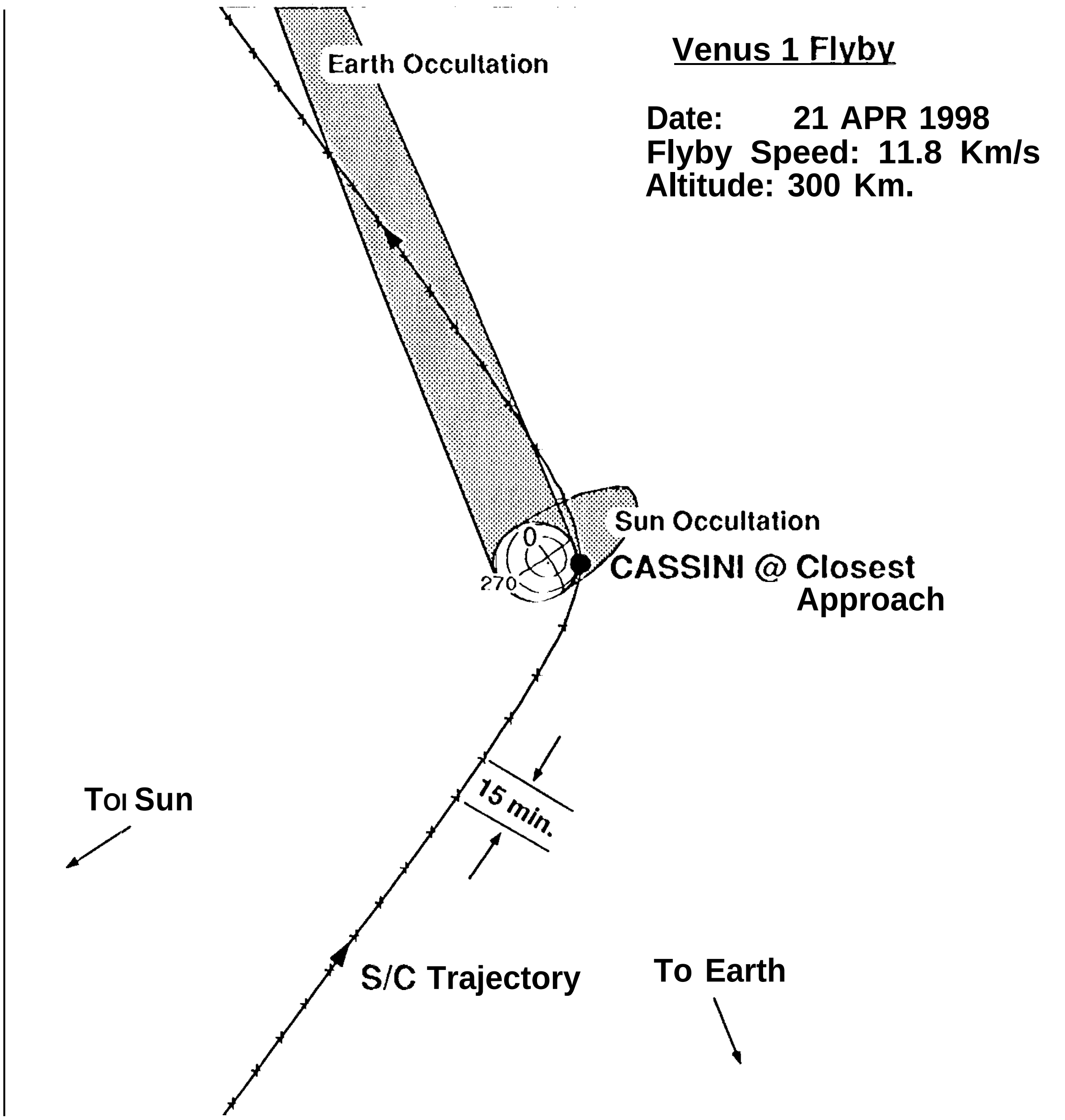

Fig. 3 VVEJGA - VENUS 1 Flyby, Trajectory North Pole View

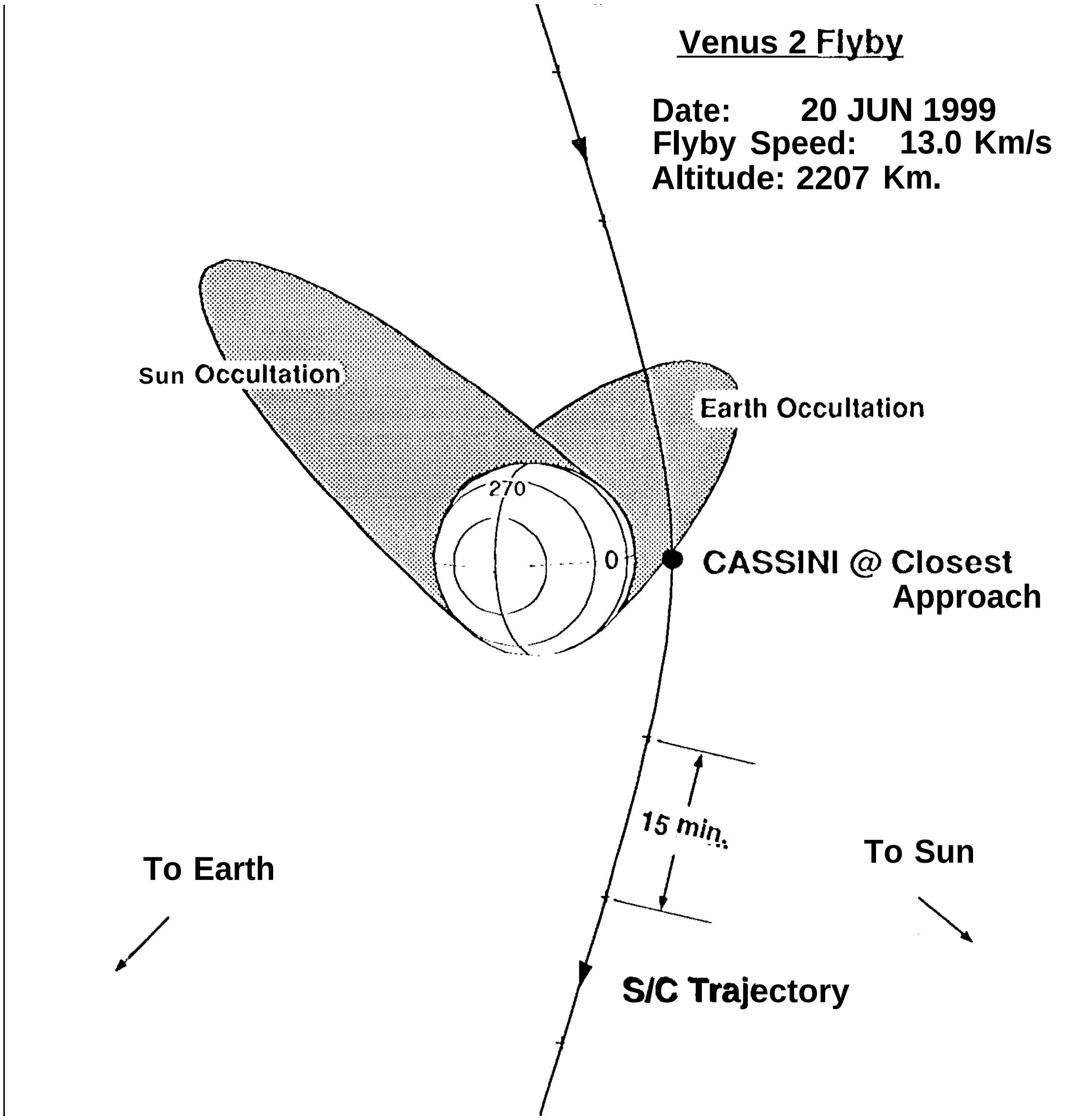

Fig. *4* VVEJGA - VENUS 2 Flyby, Trajectory South Pole View

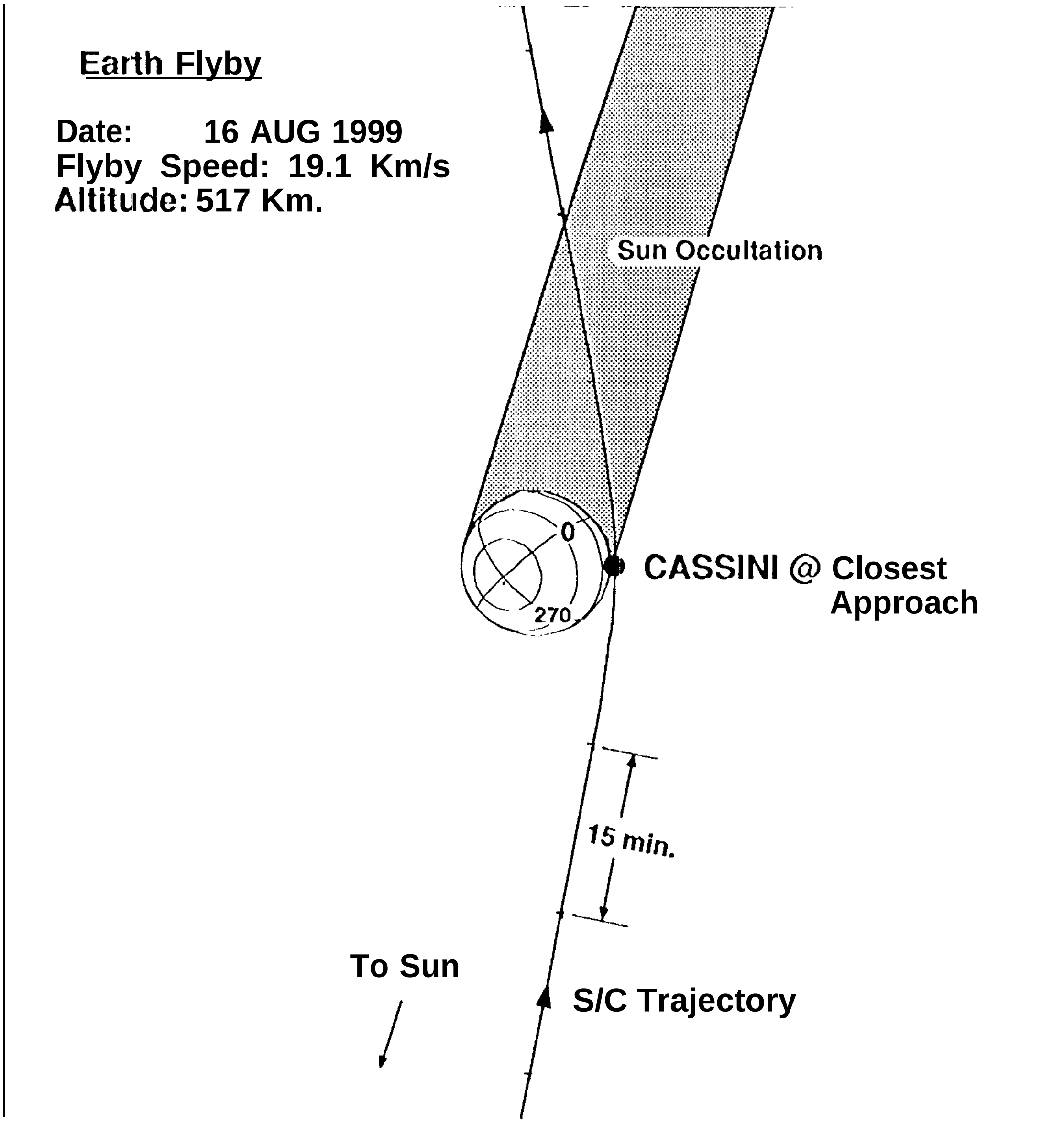

Fig. 5 VVEJGA - EARTH Flyby, Trajectory North Pole View

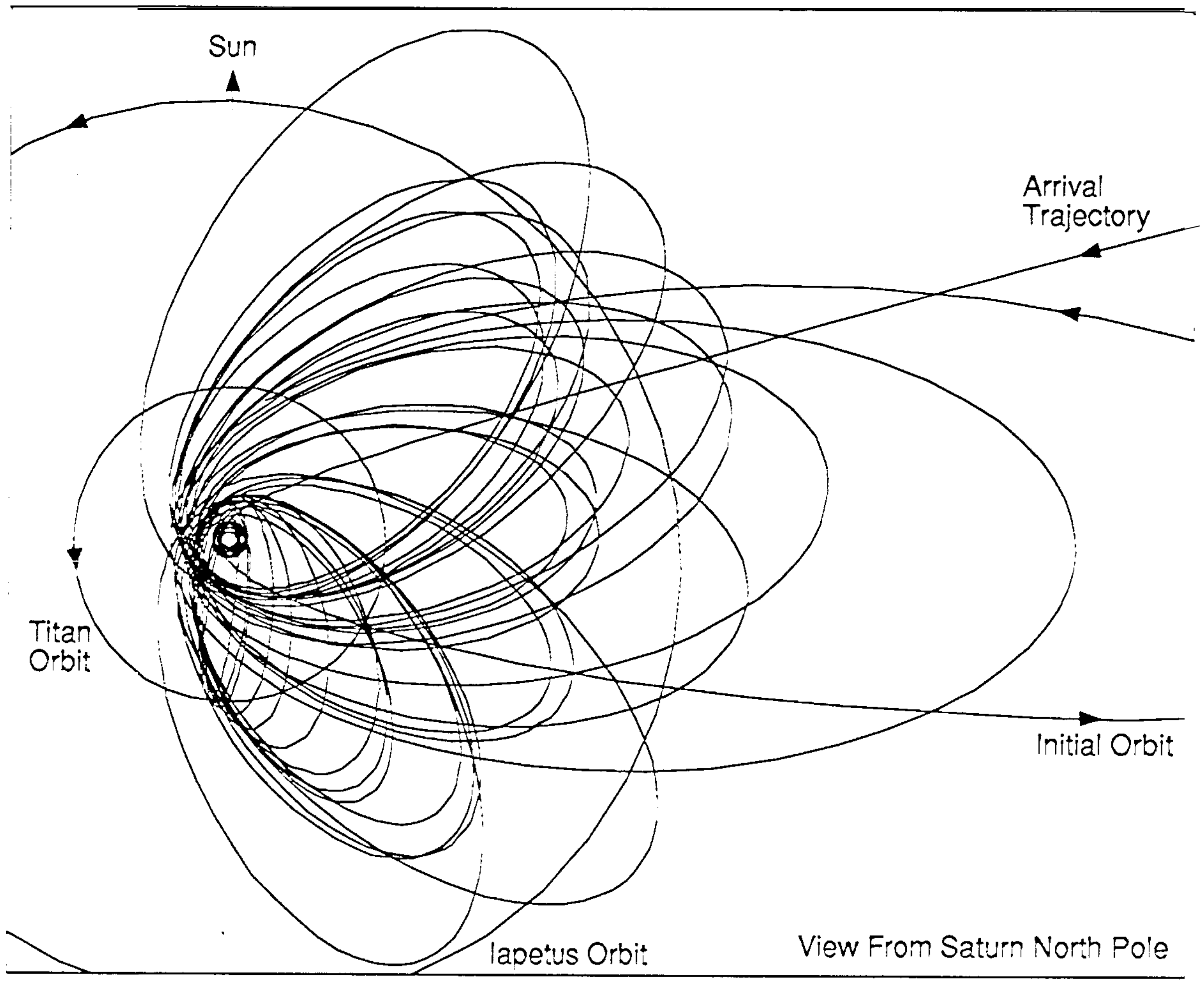

Fig 6. VVEJGA, 92-01 Orbital Tour

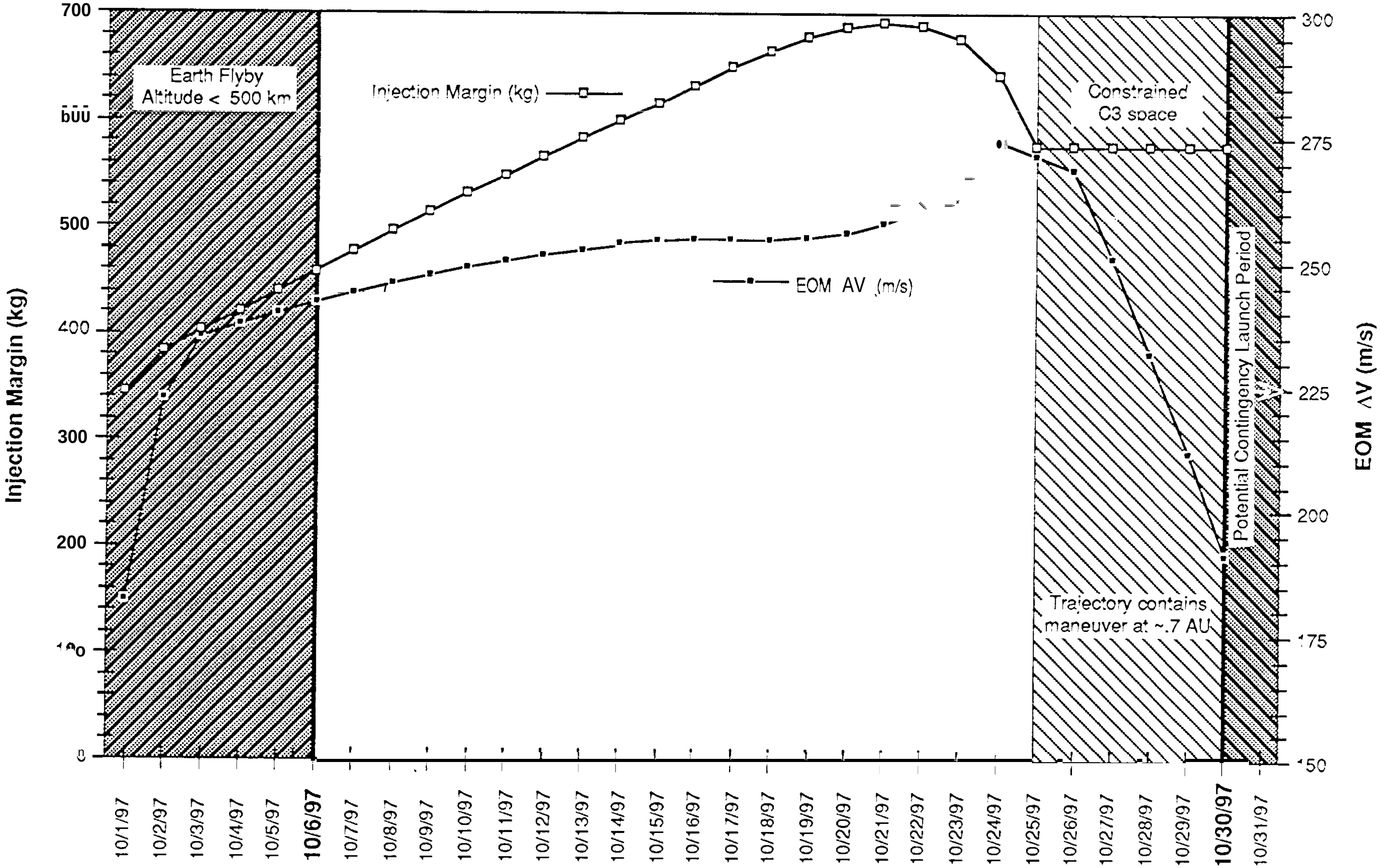

Fig. 7 VVEJGA - Injection Margin and EOM Δv as a Function of Launch Date

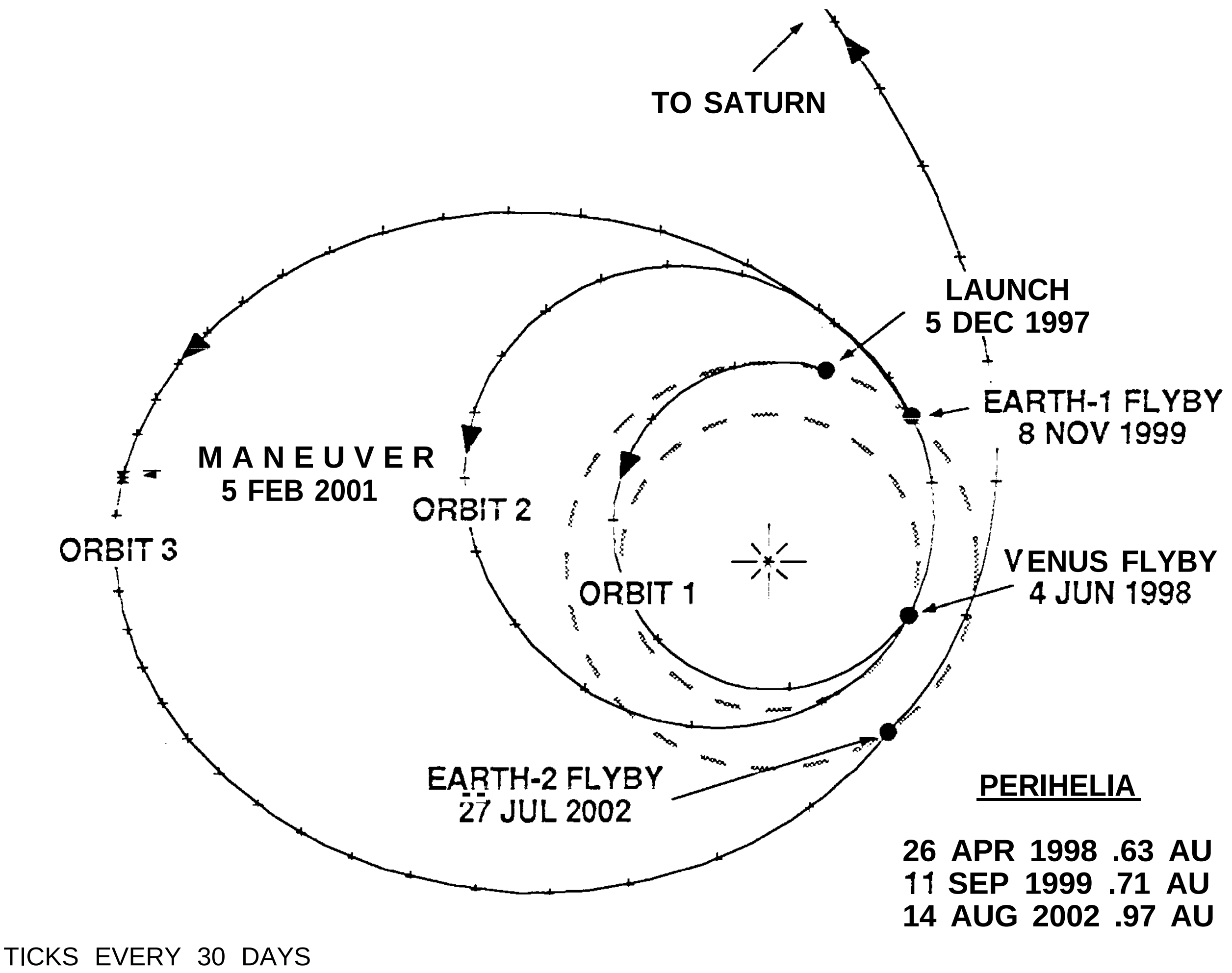

Fig. 8 VEEGA 97 - Inner Solar System Trajectory

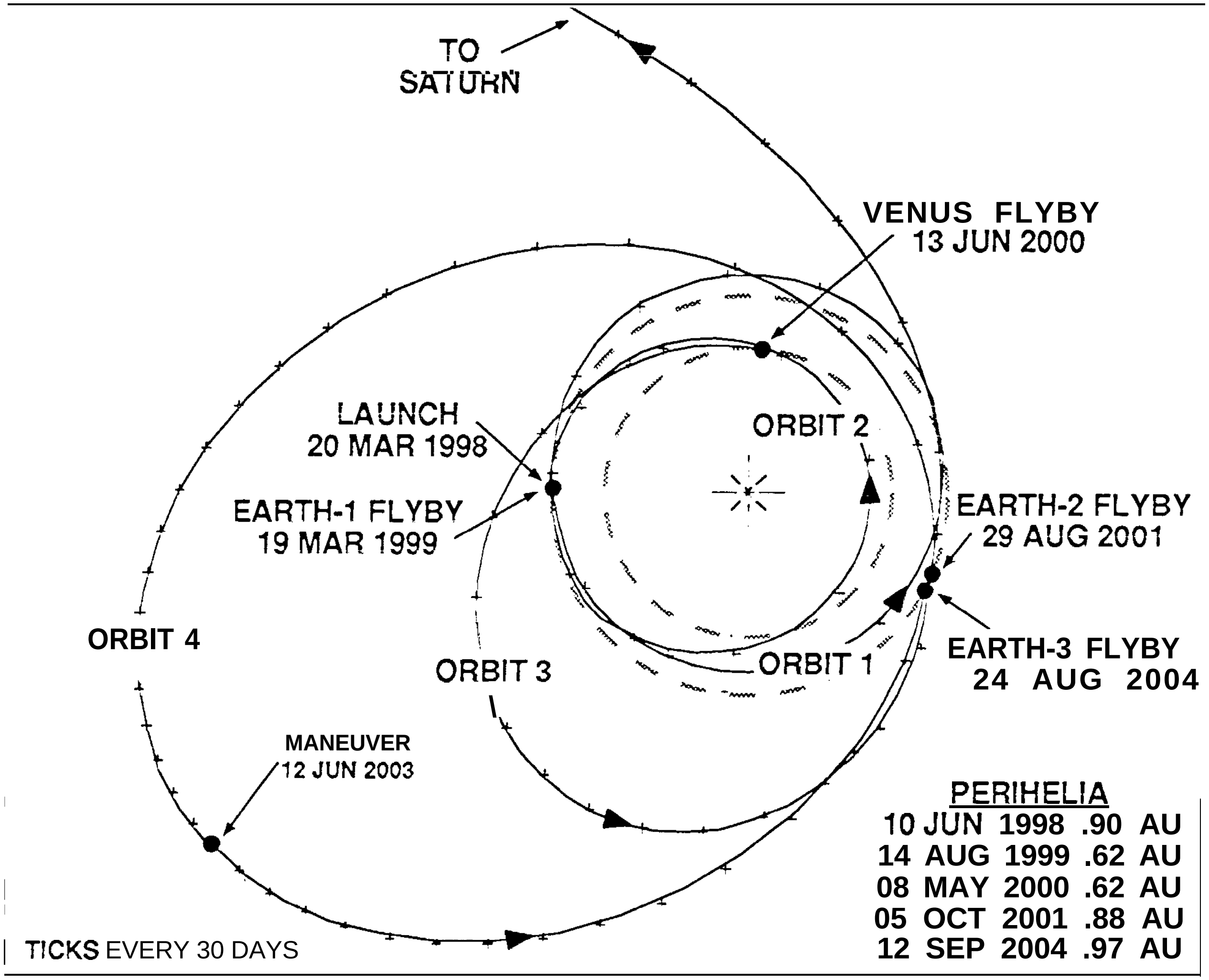

Fig. 9 EVEEGA 98 - Inner Solar System Trajectory

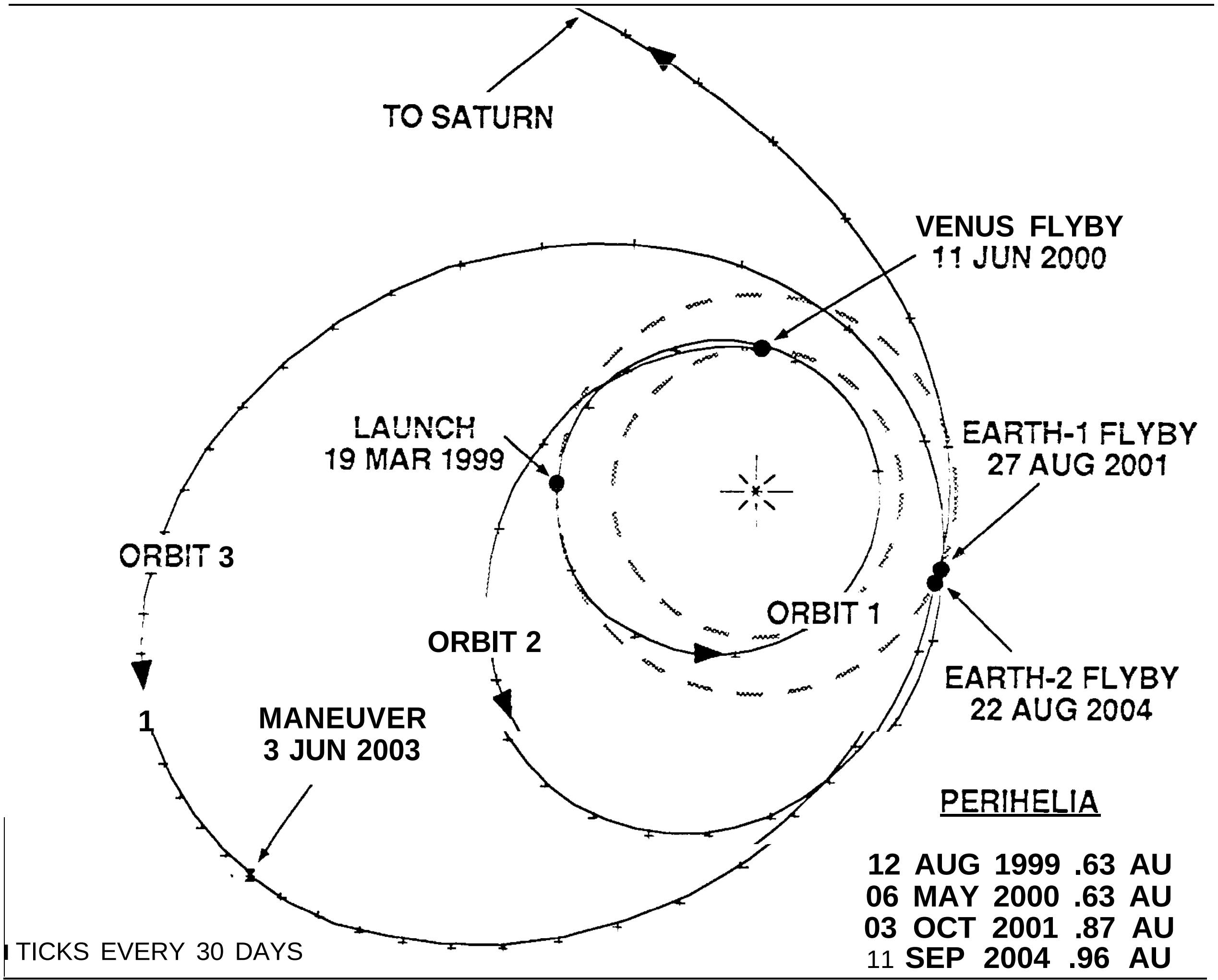

Fig. 10 VEEGA 99 - Inner Solar System Trajectory